Strangeness and charm in QCD matter

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Abstract.   Strangeness and charm degrees of freedom in strongly interacting matter are discussed within a quasi-particle model adjusted to lattice QCD data. The model allows to extrapolate lattice QCD data to large baryo-chemical potential. We outline the thermal evolution of matter in the early universe at and slightly after confinement and comment briefly on charm dynamics in relativistic heavy-ion collisions.

1. Introduction

The recent advent of numerical evaluations of the thermodynamics of strongly interacting matter, based on first principles, delivers the equation of state below and above the deconfinement temperature T_c. Equipped with this knowledge the equation of state can be extrapolated in a large region of interest. We perform here such an extrapolation employing our quasi-particle model. Having the equation of state at our disposal we consider the strangeness and charm excitations (Section 2). Then we follow the evolution of strongly interacting matter in the universe during confinement (Section 3). We address also the strangeness fraction of matter after cosmic confinement and the hadron freeze-out (Section 4). Finally we comment briefly on charm dynamics in relativistic heavy-ion collisions (Section 5).

2. Strangeness and charm in thermalized matter

Our model [1, 2] rests on the idea that strongly correlated systems can be described in terms of quasi-particles. In Fig. 1 the quasi-particle energies at vanishing momentum are shown when adjusting the model to the lattice QCD data for 2 + 1 flavors [3]. The quasi-particle energies are of the order of $0.5 \cdots 1$ GeV. Strange excitations are similar to excitations of gluons and u, d quarks. If the excitations are such massive one could argue that also charm is copiously excited. However, the interaction energy and rest mass of charm add up to such large values that charm is thermally suppressed, as expected.

In Fig. 1 also quasi-particle energies directly derived from lattice QCD evaluations [4] are depicted. These quasi-particle measurements [4] are performed for quite a different lattice configuration. The comparably large values at $1.5T_c$ (which however represent an upper limit as indicated) have been considered in [5] as hint to additional
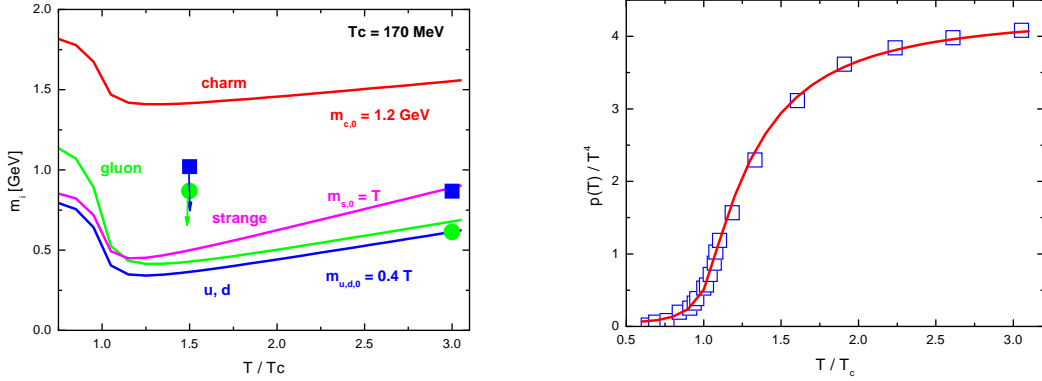
Figure 1. Energies m_i of quasi-particle excitations (left panel, quasi-particle energies from [4] are depicted by symbols) adjusted to lattice QCD data [3] for the scaled pressure p/T^4 at vanishing chemical potential (right panel).

degrees of freedom contributing to the pressure. Further dedicated measurements on the same lattices, where also the equation of state is evaluated, and in the proper momentum range $k \sim T$, which is relevant for bulk thermodynamics, are needed to clarify that issue.

Our model is successfully applicable to describe the thermodynamics of the quark-gluon fluid at non-vanishing chemical potential [2]. One can then extrapolate the equation of state into a large interval of chemical potentials not yet accessible to lattice evaluations. This knowledge is of importance for several estimates with respect to the CBM project at FAIR. Results will be reported elsewhere.

3. Cosmic confinement dynamics

The evolution of matter in an isotropic, homogeneous and flat universe is determined by the Friedmann equations and baryon conservation

$$\dot{R} = \mathcal{C}R\sqrt{e}, \quad \dot{e} = -3\mathcal{C}(e+p)\sqrt{e}, \quad (n_B R^3)\dot{} = 0, \tag{1}$$

where $\mathcal{C} = \sqrt{8\pi/3}/M_{Pl}$ with M_{Pl} as Planck mass, R stands for the scale factor, and p, e and n_B denote the pressure, energy density and baryon density, respectively. In the early universe $\mu/T \ll 1$ due to $\eta \equiv (n_\gamma/n_B)_0 \approx 10^{10}$. Being aware of the need of a systematical chiral extrapolation, we tentatively employ the parametrization described in Section 2 and extend to finite chemical potential μ [2] with $T_c = 170$ MeV. Adding the background of leptons and photons we arrive at the results displayed in Fig. 2. In contrast to the bag model, the temperature is continuously dropping at confinement (left panel). The differences of the time evolution of the scale factor are tiny for various scenarios (middle panel). In [6] it was argued that a strong supercooling with dominating vacuum energy, represented by the bag constant, could cause a mini-inflationary era. With the present equation of state such a scenario is unlikely.

The bag model equation of state would deliver a large difference of baryon densities under equilibrium condition (equal temperatures, chemical potentials and pressures) in the confined and deconfined phases (right panel). It was thought that in a
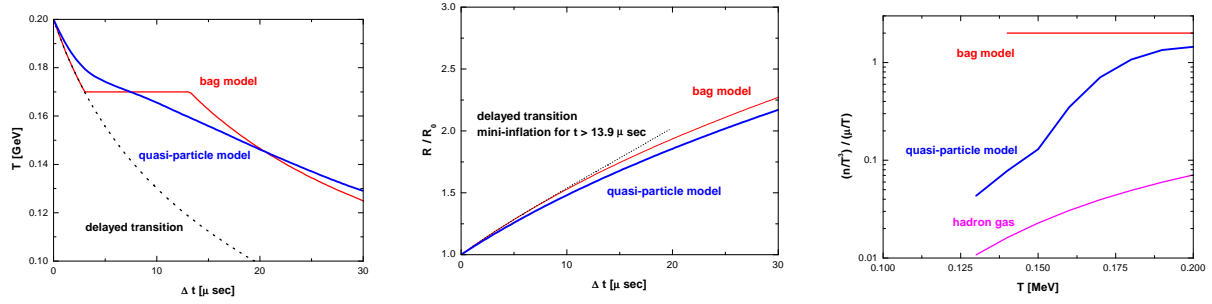
Figure 2. Temperature T (left panel) and scale factor R (middle panel) as a function of the time (with zero point arbitrarily adjusted at $T = 200$ MeV). The right panel exhibits the scaled baryon density $n/T^3(\mu_q/T)^{-1}$ as a function of the temperature.

departure from equilibrium at the end of the confinement transition the baryon charge is concentrated in the last islands of the deconfined matter which afterwards transforms to energetically more favorable strange matter [7]. The present equation of state from lattice QCD, however, disfavors such a scenario.

4. Cosmic hadron freeze-out

The evolution of the strongly interacting matter component in the early universe can further be followed by employing the resonance gas model. Note that the total energy density and pressure below T_c are dominated by leptons and photons. In Fig. 3 various quantities of interest are exhibited. In the upper left panel the densities of a few selected hadrons are depicted. Pions dominate some time, kaons are subdominant, open charm is completely negligible. The tiny baryon excess, described by the present photon-to-baryon ratio $\eta \approx 10^{10}$ is unimportant down to temperatures $\mathcal{O}(40$ MeV), i.e., the densities of baryons (N) and anti-baryons $(a - N)$ are nearly the same. Below 40 MeV, however, baryon conservation drives the chemical potential towards 1 GeV (upper right panel) causing a constant comoving baryon density, while the anti-baryon density drops rapidly. This explains the disappearance of anti-matter. Briefly after confinement the baryon component was quite strange: About 30% of the baryons, constituting now the hard core of visible matter in the universe, were in form of Λs (lower left panel).

It is often claimed that matter is produced in relativistic heavy-ion experiments under similar circumstances as in the early universe. While at RHIC, at chemical freeze-out, a baryo-chemical potential $\mathcal{O}(10$ MeV) is found [8], in the early universe, at comparable temperatures, the chemical potential is $\mathcal{O}(1$ eV) (upper right panel, cf. also [9]). Besides, there is a factor 10^{18} difference in time scales (lower right panel).

5. Charm dynamics at RHIC

Our finding in Section 2 suggests that charm is not noticeably created by thermal excitations at physically relevant temperatures. Rather, charm is created by hard
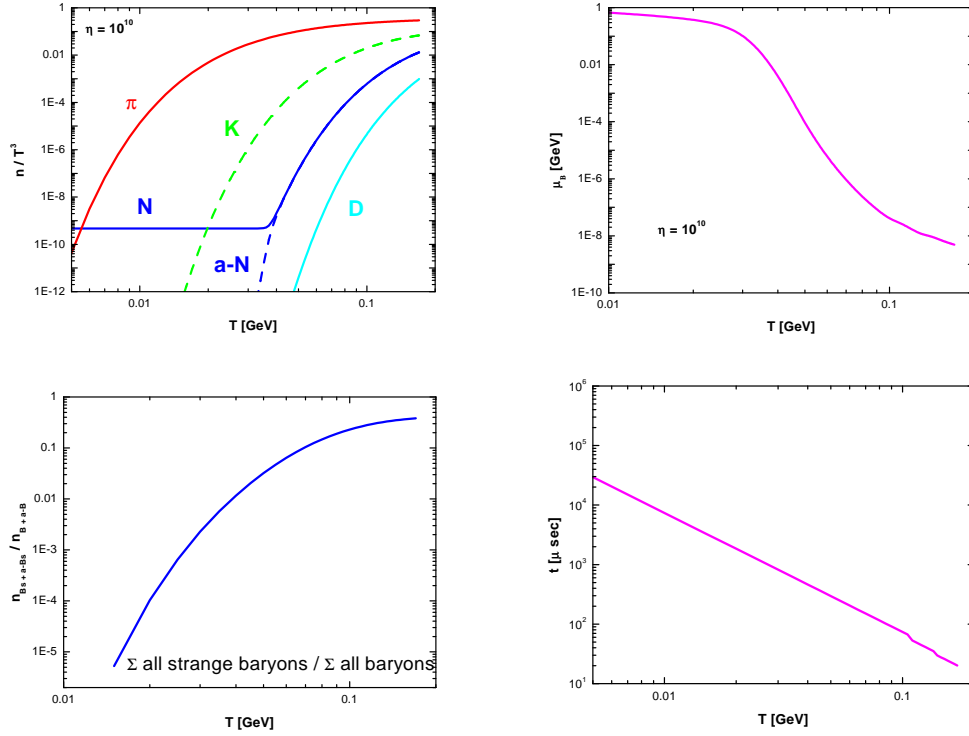
Figure 3. Temperature dependence of scaled densities of selected hadrons (upper left panel), baryo-chemical potential (upper right panel), ratio of strange baryons to all baryons (lower left panel), and elapsing time (lower right panel).

processes in the initial stage of heavy-ion collisions. One interesting question concerns the energy loss of charm quarks. Due to the semileptonic decays of D mesons the momentum distribution of inclusive decay electrons should be modified by the energy loss. Our first analysis [10] did not evidence a signal for such an energy loss. It could be that the dead cone effect [11], the Ter-Mikaelian effect [12] and the Landau-Pomeranchuk effect (cf. [13]) suppress the energy loss. As shown in [10], the di-electrons from correlated semileptonic decays of open charm are more sensitive to energy loss effects. The recent run-4 results at RHIC will shed further light on that issue.

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